

Top Mass Measurements and Non-perturbative QCD Effects



Daniel Wicke
(Bergische Universität Wuppertal)



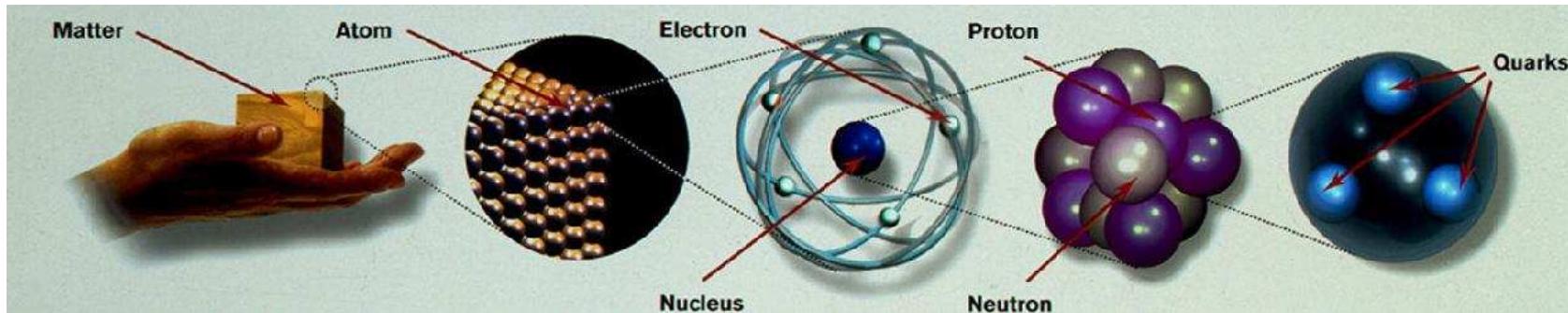
Outline

- Introduction
- Measuring the Top Mass
- Modelling in Hadron Collisions
- Influence of CR and UE
- Conclusions

Introduction

- the Standard Model of particle physics
- top quark physics
- experimental environment

The Standard Model of Elementary Particle Physics



Matter

e electron

ν_e electron neutrino

u up-quark

d down-quark

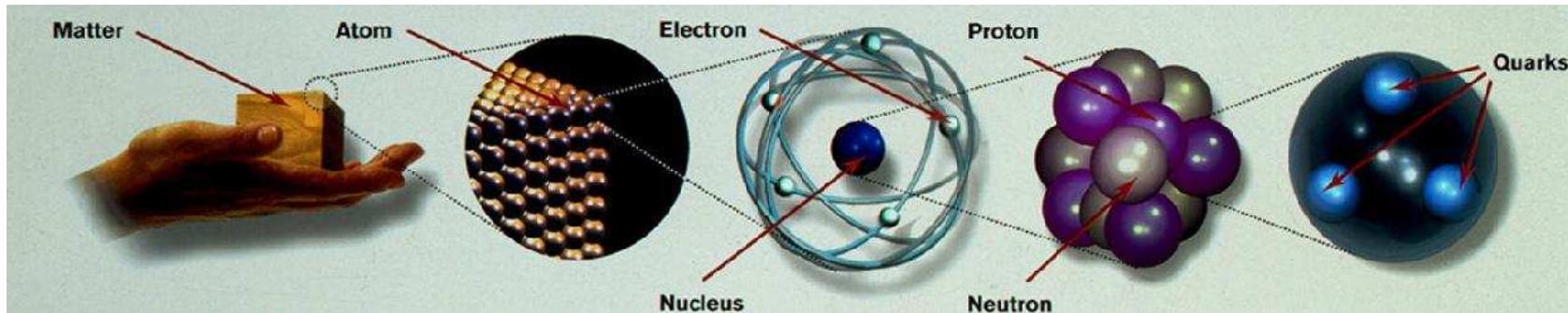
Forces

Electromagnetism: Photon γ ,

Weak force: Z, W^\pm ,

Strong force: Gluon g

The Standard Model of Elementary Particle Physics



Three families of matter

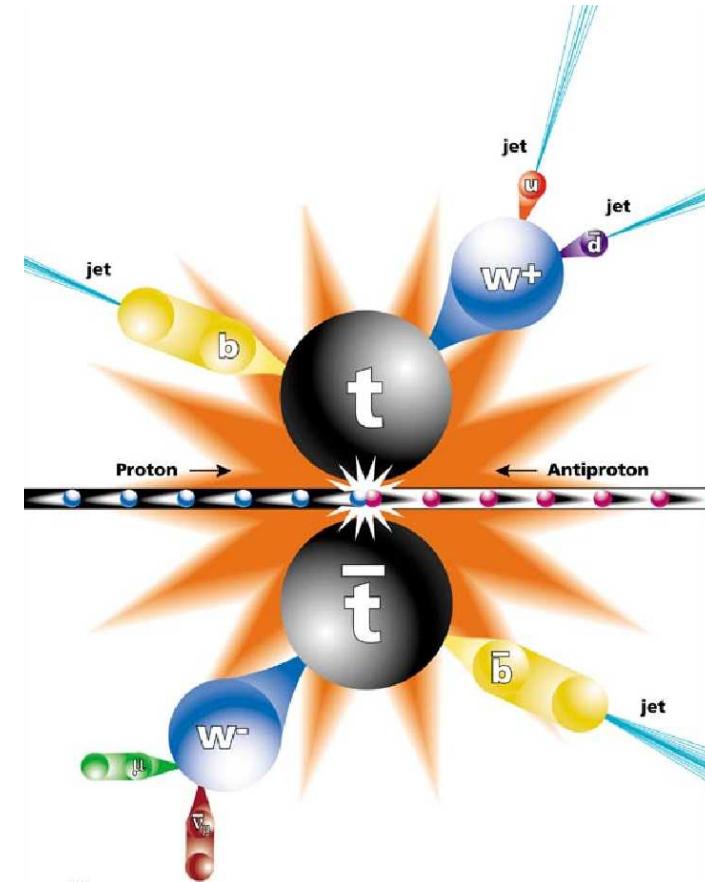
e	electron	μ	muon	τ	tauon
ν_e	electron neutrino	ν_μ	muon neutrino	ν_τ	tau neutrino
u	up-quark	c	charm-quark	t	top-quark
d	down-quark	s	strange-quark	b	bottom-quark

Forces

Electromagnetism: Photon γ , Weak force: Z, W^\pm , Strong force: Gluon g

The Top Quark

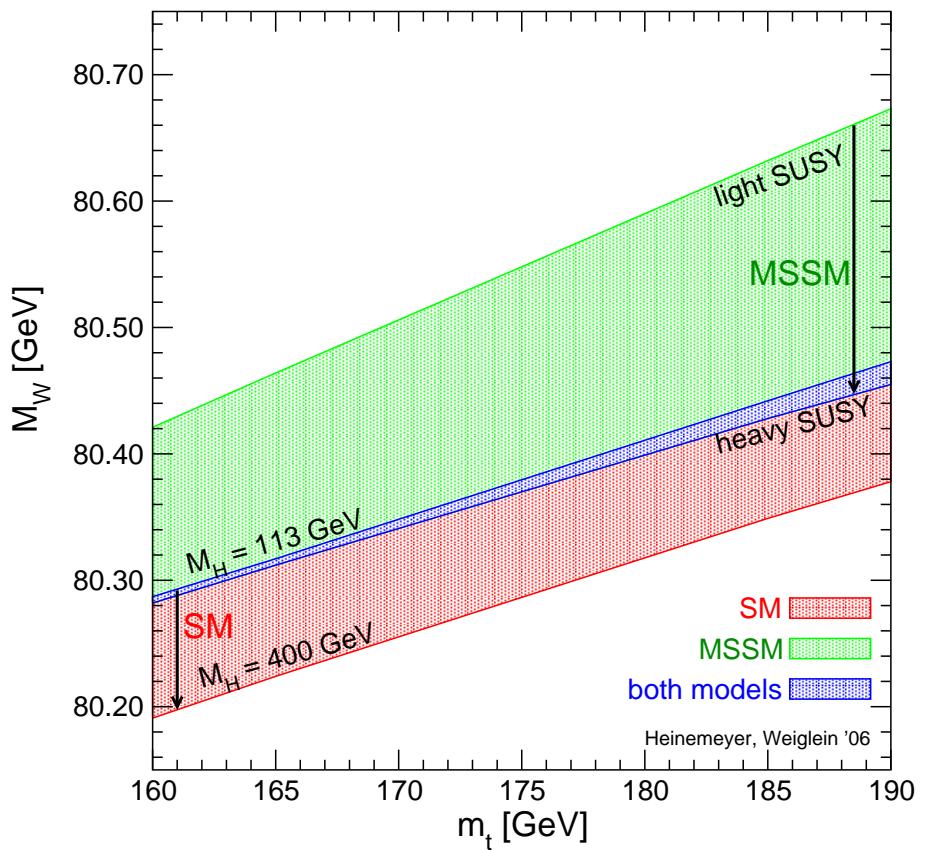
- Discovered by CDF and DØ in 1995.
- Completes set of quarks in SM.
- Quantum numbers as for up-type quarks.
- Only its mass is a free parameter.
- Production and decay properties fully defined in Standard Model.



Only few of its predicted properties verified

Relevance of the Top Mass

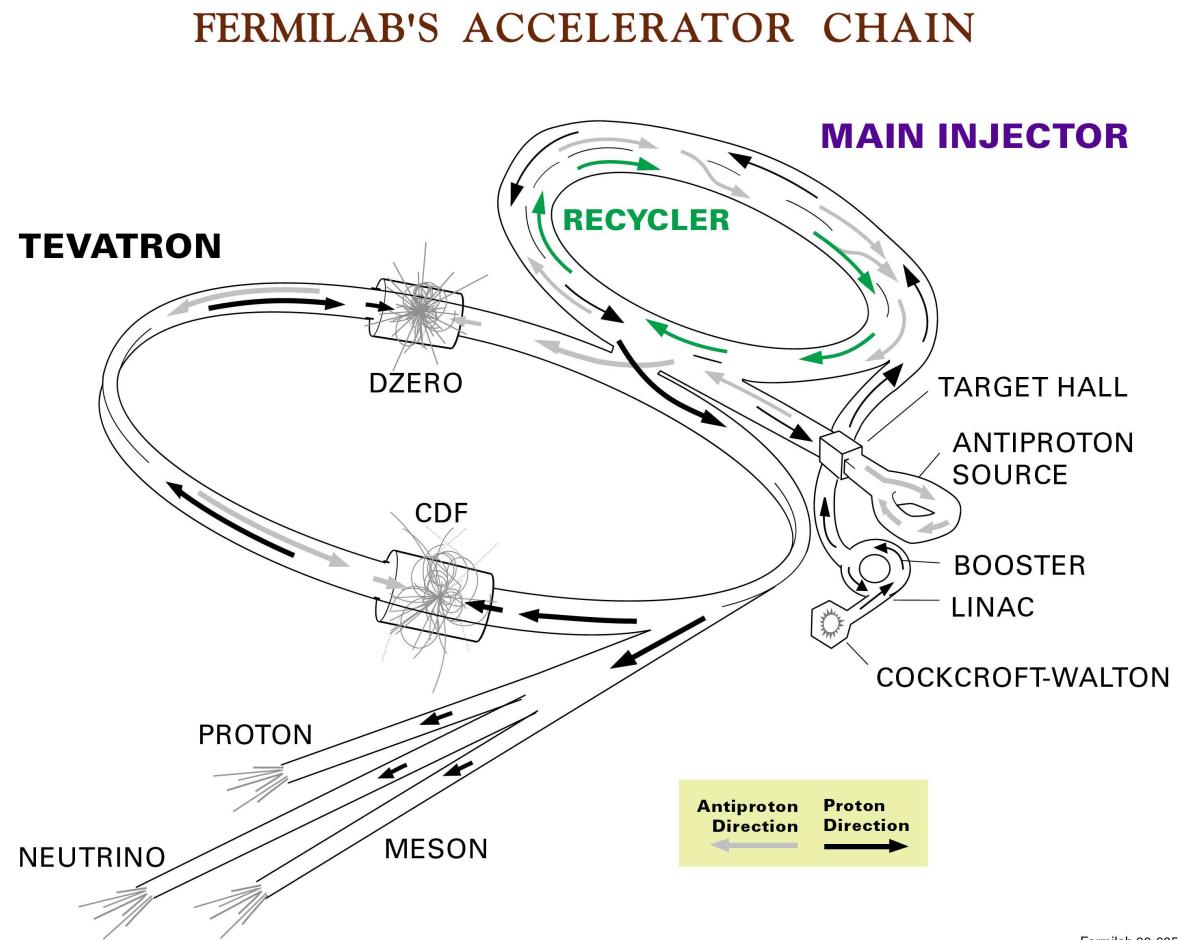
- Radiative corrections to electro-weak observables depend on the Top Mass.
- Allow prediction of the Higgs Mass
 - Differentiate between SM and extended Models.
- After Higgs discovery:
 - Consistency check of SM.



Experimental Environment

The $p\bar{p}$ Accelerator Tevatron

- Circumference 7 km.
- $p\bar{p}$ collisions
- Run I (1987-1995)
- Run II (since 2001)
Collision energy 2 TeV
- 2 experiments,
CDF and D \emptyset ,
record events.



The Tevatron



The (DØ) Detector

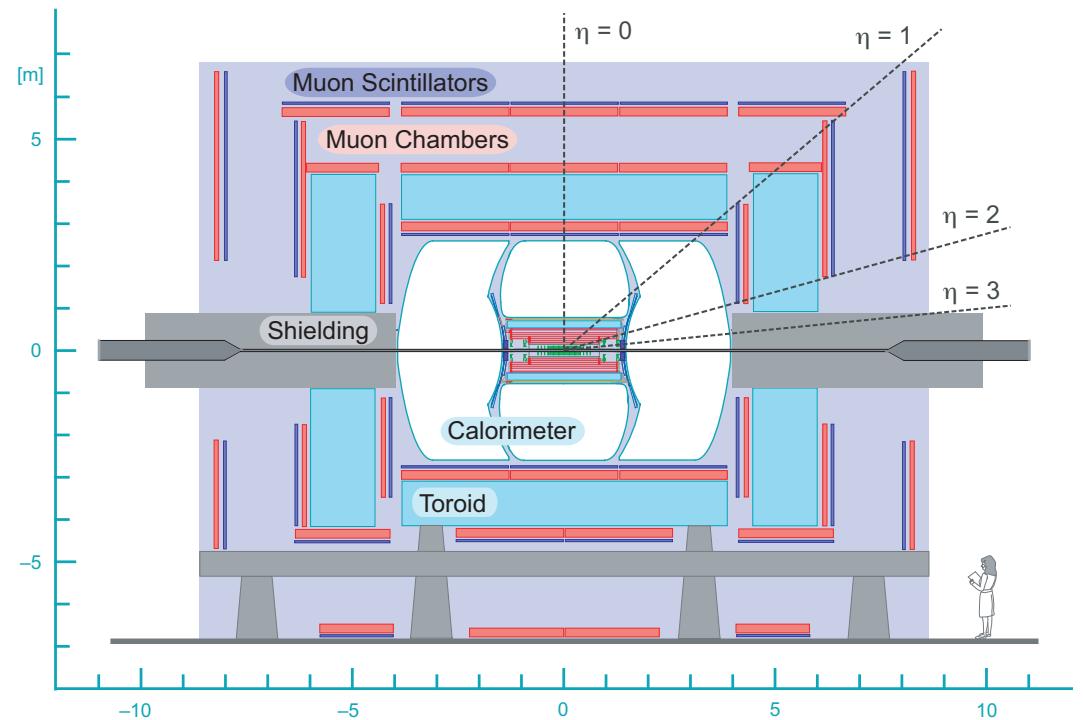
A 4π general purpose detector:

- Tracking in 2T solenoid
 - Silicon microstrip
 - Scintillating fiber tracker
- Calorimetry
 - Uranium/liquid argon
- Muon spectrometer
 - 3 layers of drift tubes
 - Toroidal magnetic field
(1.9T between inner 2 layers)

Dimensions: $12 \times 12 \times 20 \text{m}^3$

Note: Polarangle θ against beam axis

$$\text{Pseudorapidity } \eta = -\ln \tan \theta/2$$



Reconstructed Physics Objects

Muon

Track in Muon chambers (outside the calorimeters)

Electron

Energy deposition only in the innermost ('em') calorimeter part.

Jets (sign of quarks or gluons)

Accumulations of energy deposited in the 'hadron' calorimeters.
CDF and DØ usually use Cone jet algorithms.

Missing Transvers Energy, \cancel{E}_T (sign of neutrinos)

Negative sum of all energy measured transverse to beam directions

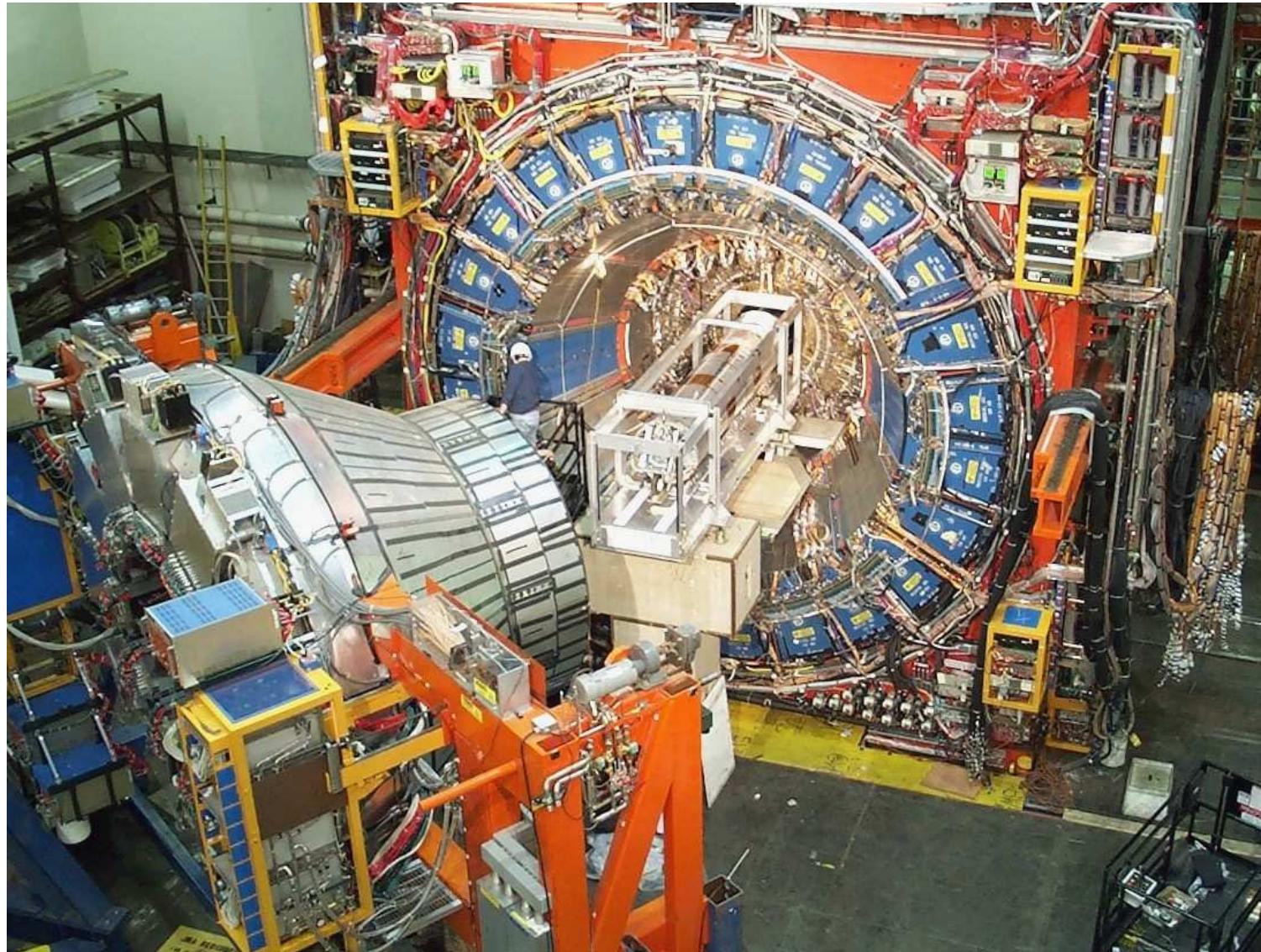
B-Tag (sign of *b*-quarks)

Long lifetime of *B*-Hadrons lead to secondary vertices, detected with tracking.

- International collaboration
- 90 institutes, ~ 700 physicists
- 18 countries from 4 continents

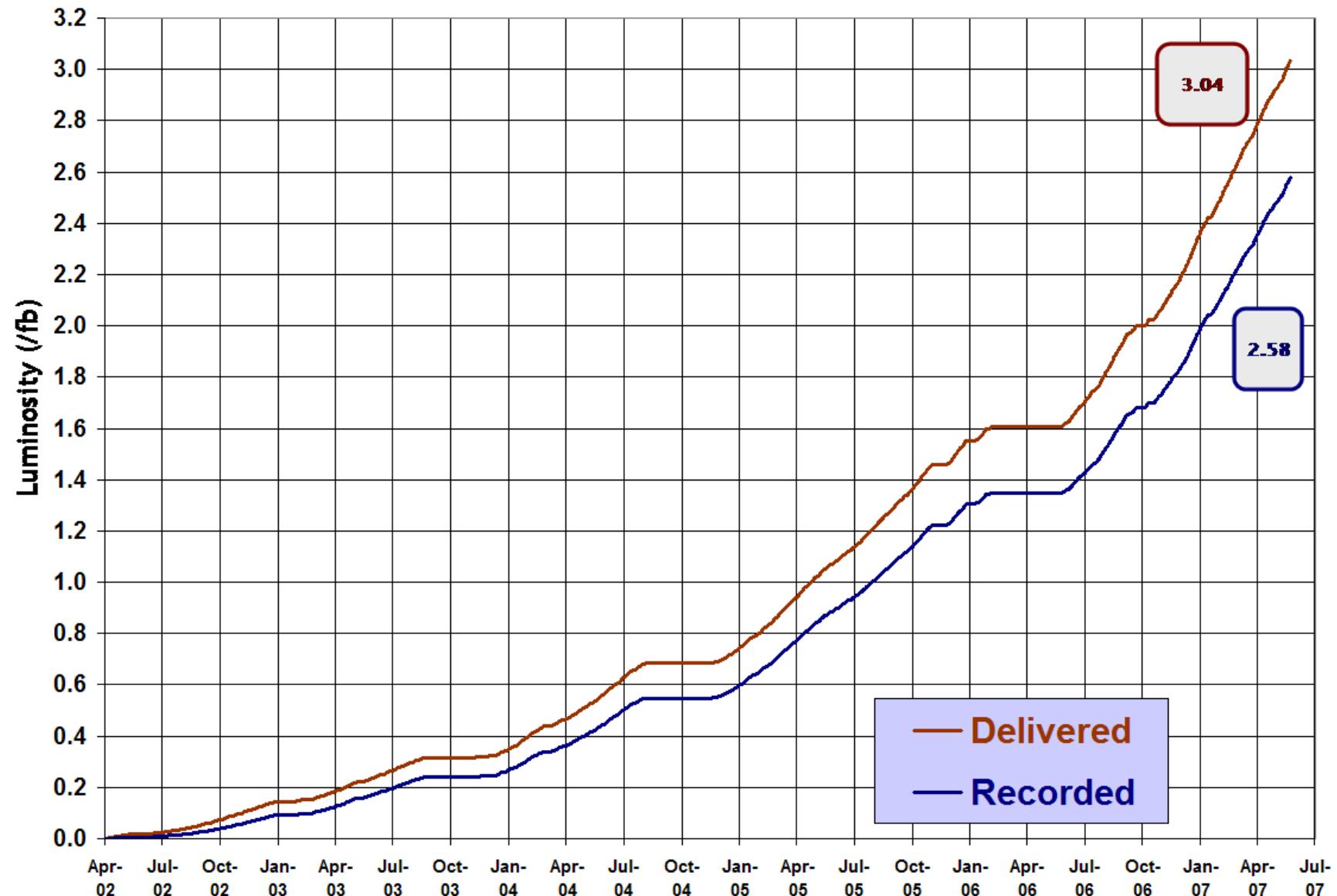


CDF



DØ RunII Integrated Luminosity

Apr 2002 – June 2007

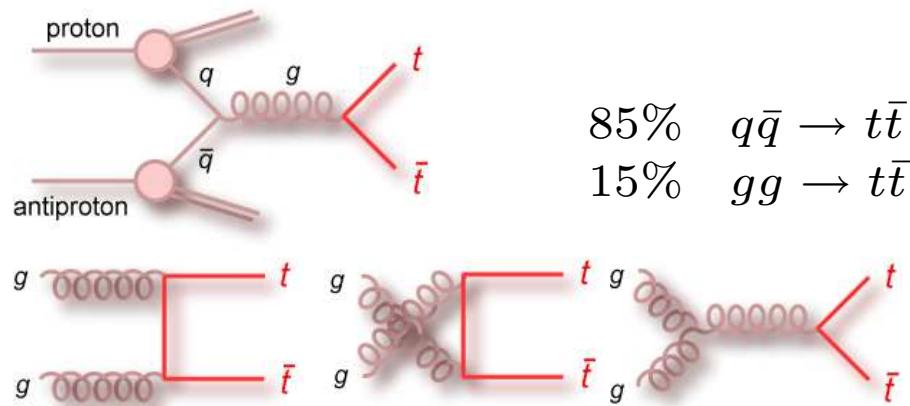


Top Mass Measurements

- Top Pairs and its Signatures
- Methods in Semileptonic Channel
- Combined Results and Outlook

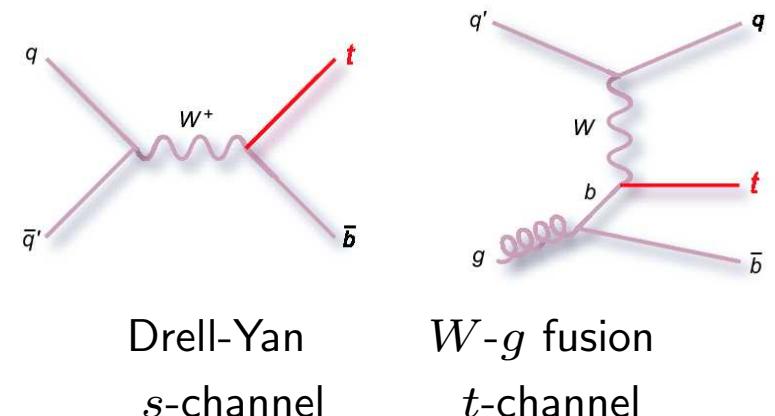
Top Quark Production at the Tevatron

Strong top production



- $\sigma(t\bar{t}) = 6.77 \pm 0.42 \text{ pb}$

Weak top production



- $\sigma(t) = 2.9 \pm 0.3 \text{ pb}$

For integrated luminosity of $\sim 1 \text{ fb}^{-1}$

around 7000 top pairs and 3000 single tops expected.

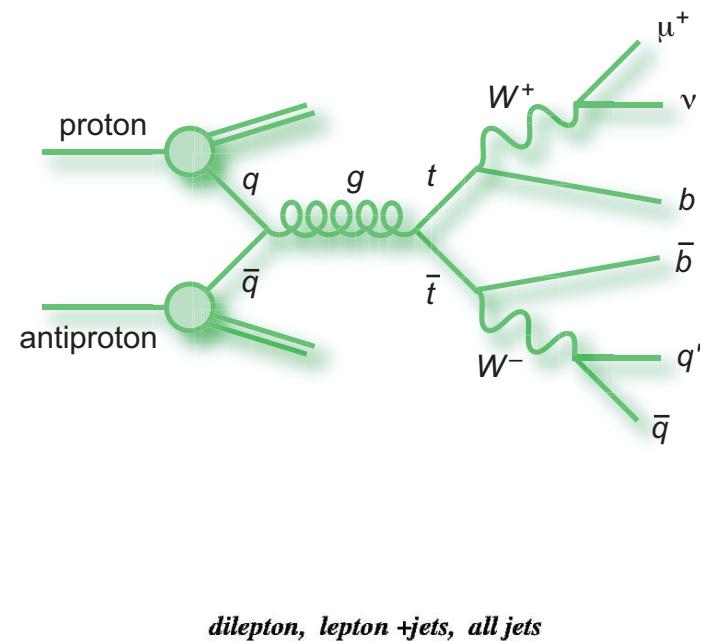
Top Quark Decay

Top quarks decay to bW (nearly) 100%.

Pair Production Signatures

Decay modes are defined by W -decays:

- Dilepton $(2b + 2l + 2\nu)$
- Lepton+jets $(2b + 2q + l\nu)$
- Alljets $(2b + 4q)$

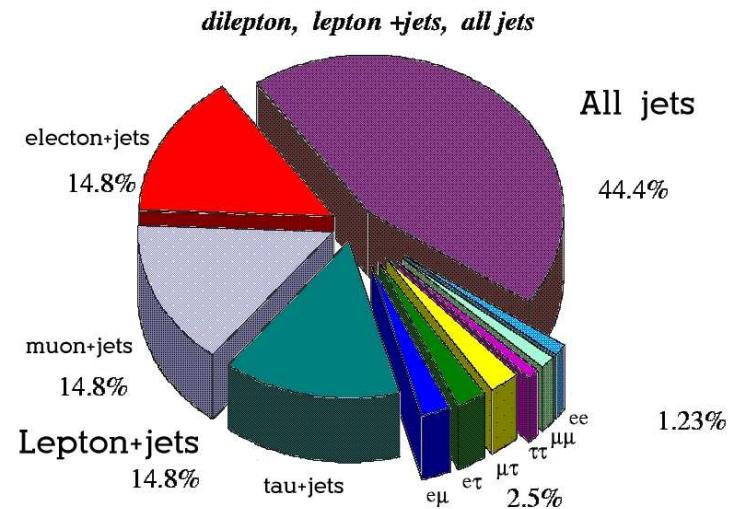


Single Top Signatures

Defined by W -decays and channel;

e.g. leptonic decay:

- s-channel $(2b + l + \nu)$
- t-channel $(b + j + l + \nu)$



Signature and Selection in Semileptonic Channel

Signal Signature

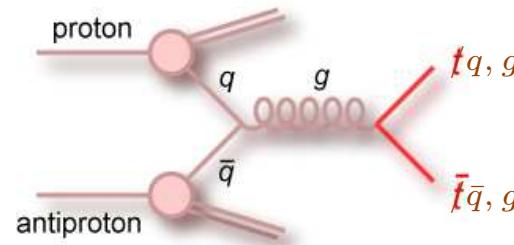
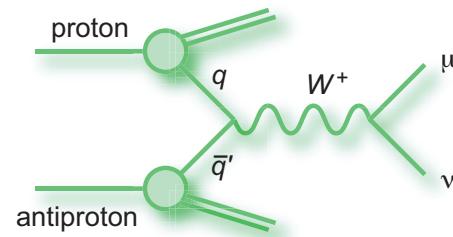
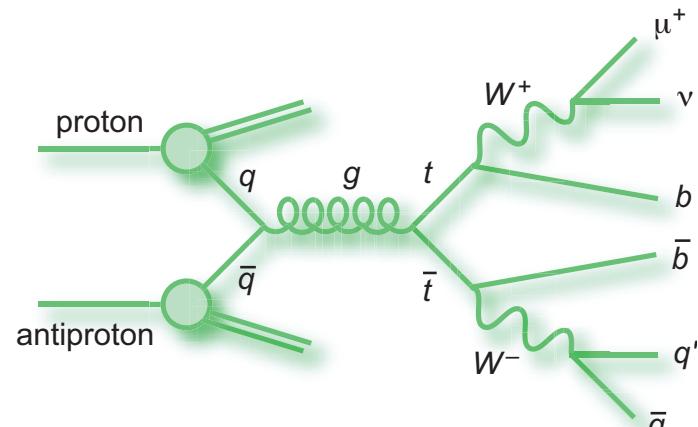
- Lepton (e, μ)
- Neutrino (\not{E}_T)
- min. 4 Jets (2 from b -quarks)

(Pre)Selection

- Selection based on cross-section
- 4 jets, iso. Lepton, $\not{E}_T; > 20$ GeV each.

Background Classes

- W +jets; physical background
- Multijet (QCD); instrumental bkg.



Methods in Semileptonic Channel

Template Method (CDF)

Signal Sample

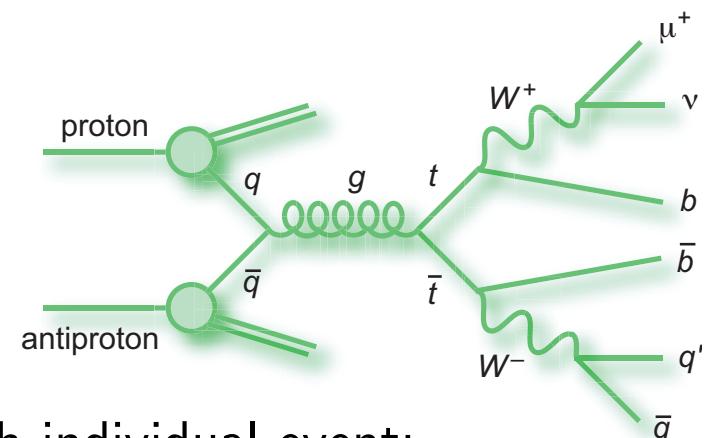
- Four separate event types:
0 b -tag, 1 b -tag loose, 1 b -tag tight, 2 b -tag

Top mass determination

Reconstruct four-momenta of t -Quarks in each individual event:

- Reconstruction of ν momentum
- (Correct) association of $l\nu$ and 4 jets to 2 top-quarks
- Sum of associated four-momenta is $m^2 = E^2 - \vec{p}^2$

In reality done with fit: Same top-mass and nominal m_W as constraints.
Precise energy measurement & correct association crucial:
 $\min. \chi^2$ solution used.



Top mass determination (2)

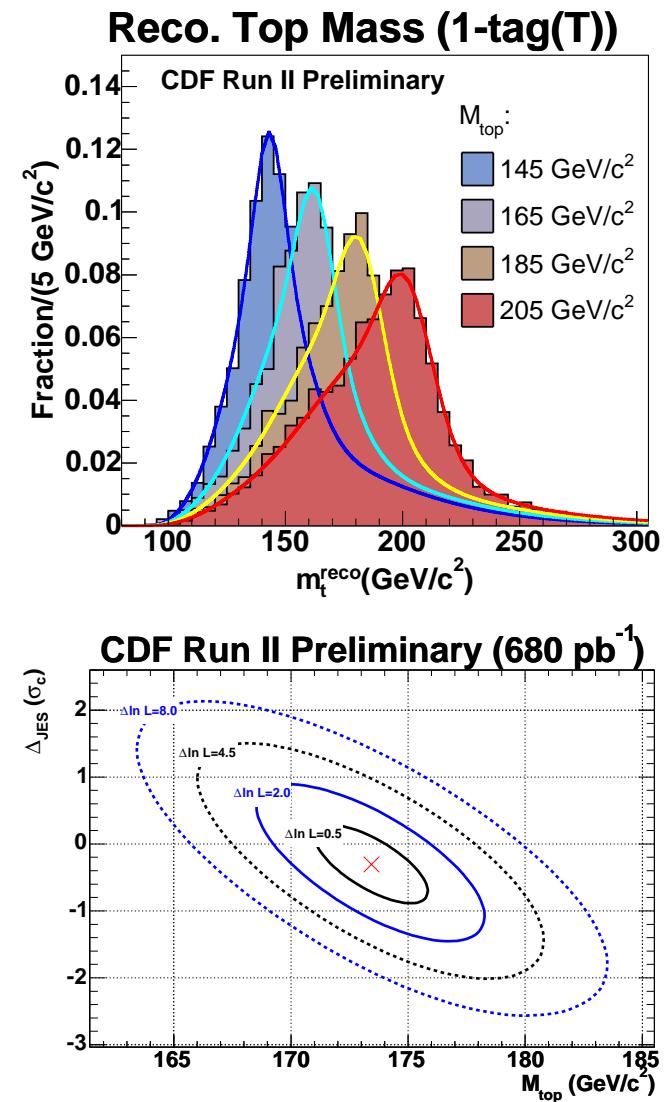
- Build histogramm of top-masses.
- Compare with simulation (Templates)
 - for various m_t und JES.
 - including expected Background.
- Find m_t with best agreement.

Restriction of JES

- Templates for m_W reconstructed from m_{jj} .
- Fit without constraints.
- All pairs of non-b-tagged jets.

Top-mass and JES from 2d-Fit (680 pb^{-1}):

$$m_t = 173.4 \pm 2.5(\text{stat + JES}) \pm 1.3(\text{syst}) \text{ GeV}$$



Ideogramm Method (D \emptyset)

- Reconstruct m_t in each individual event (as in template method).
- Compute weight (probability) for each event and each association.

$$P_{\text{evt}}(x; m_t) = f_{\text{top}} P_{\text{sgn}}(x; m_t) + (1 - f_{\text{top}}) P_{\text{bkg}}(x)$$

$$P_{\text{sgn}}(x; m_t) = \sum_{\text{Combinations}} w_i \left(f \int_{100}^{300} \underbrace{\mathbf{BW}(m', m_t)}_{\text{rel. Breit-Wigner}} \underbrace{\mathbf{G}(m', m_t, \sigma_i)}_{\text{exp. resolution}} dm' + \underbrace{(1 - f) S(m_i, m_t)}_{\text{wrong combinations}} \right)$$

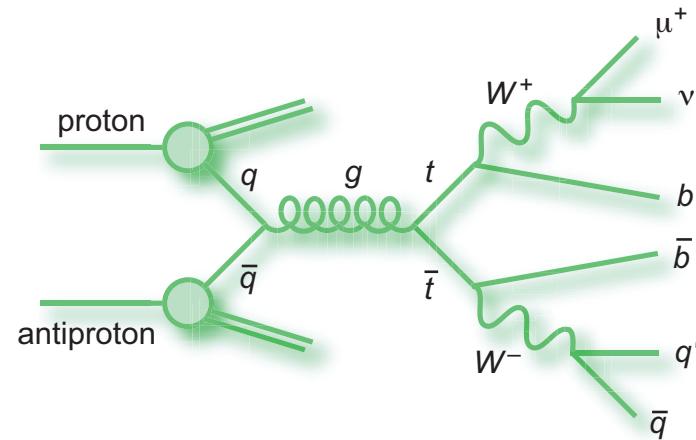
- Product of event prob. yields sample probability as function of m_t .
- Maximising the sample probability yields:

$$173.7 \pm 4.4(\text{stat}) \pm 2.1(\text{syst}) \text{ GeV} \quad (420 \text{ pb}^{-1})$$

- Uses information from „wrong“ associations and from events with > 4 jets.

Matrix Element Method

Probability for each kinematic configuration x
as function of m_t :



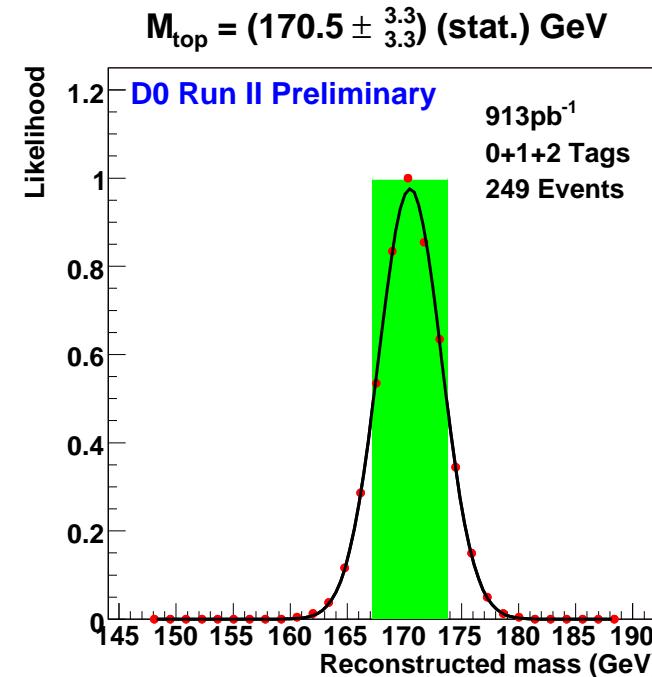
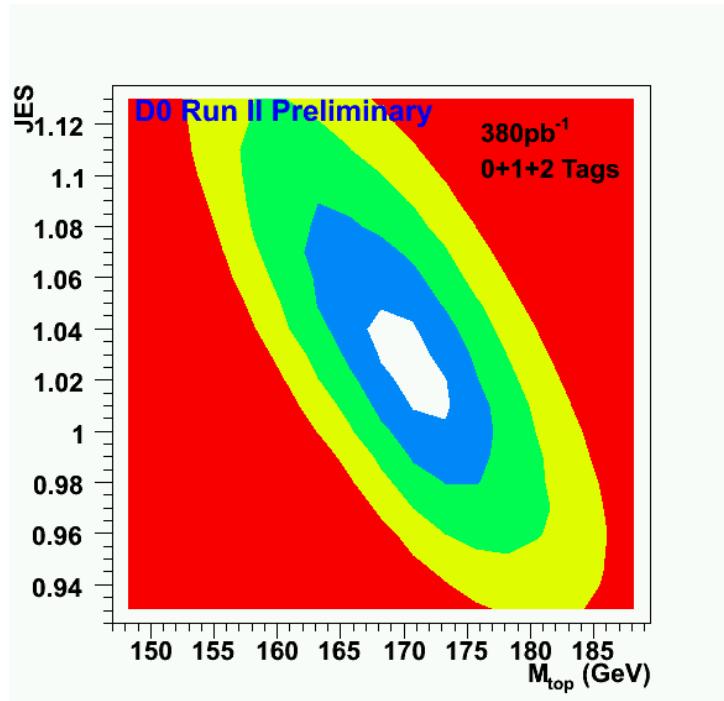
$$P_{\text{evt}}(x; m_t) = f_{\text{top}} P_{\text{sgn}}(x; m_t) + (1 - f_{\text{top}}) P_{\text{bkg}}(x)$$

$$P_{\text{sgn}}(x; m_t) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int dq_1 dq_2 \underbrace{d^n \sigma(q\bar{q} \rightarrow t\bar{t} \rightarrow y; m_t)}_{\text{matrix element}} \underbrace{f(q_1)f(q_2)}_{\text{PDFs}} \underbrace{W(y, x; \text{JES})}_{\text{resolution}}$$

- ME uses $q\bar{q} \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow W + \text{jets}$. Multijet treated as syst. uncertainty
- Extended to determine Jet Energie Skala in-situ simultaneously
(dominating uncertainty)

Matrix Element Method Results (D \emptyset)

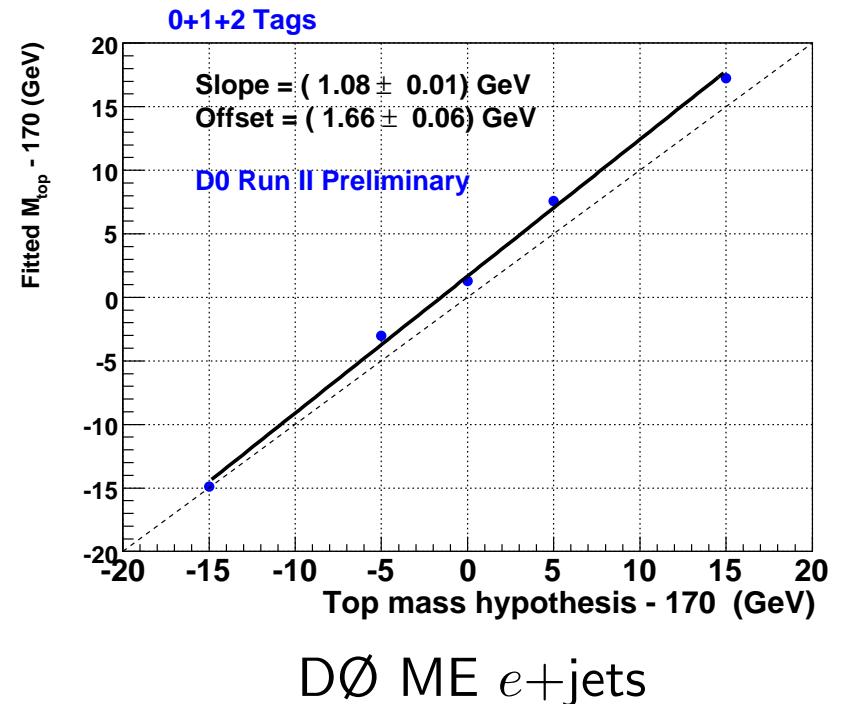
Find optimal m_t (and JES) given observed data,
i.e. maximise product of probabilities of all events:



$$m_t = 170.5 \pm 2.4(\text{stat} + \text{JES}) \pm 1.2(\text{syst}) \text{ GeV} \quad (\text{b-tagged}, 910 \text{ pb}^{-1})$$

Ensemble Testing

- To verify these machineries, test with many sets of **pseudo-data**.
- Wonderful tool to test analysis methods! Run DØ experiment 1000s of times!
With various top mass values and JES-factors, too.
- Check response of each analysis to various input parameters.
- *Calibrate* “response” to input m_t , JES.
- Done for each analysis.



Summary of Methods in Semileptonic Channel

- Template Method (CDF, DØ)
 m_t reconstruction in each event, one or more associations, all events equally important.
- Ideogramm Method (DØ)
 m_t reconstruction in each event, all associations of an event enter with weights.
- Matrix Element Method, Dynamic Likelihood (CDF, DØ)
all associations of an event enter with weights, uses angular information.

All methods use

- Mass estimator (explicit or implicit)
 - Reconstructed physics objects
 - Jet assignment (choose or weight)
- JES correction factor
- Calibration

Kombination der Resultate

TeVWWG kombiniert RunI und RunII Ergebnisse beider Experimente.
Best Linear Unbiased Estimator (BLUE), d.h. berücksichtigt Korrelationen.

Systematische Unsicherheiten

- Jet Energie Skala (leichte Quarks)
weiterhin dominierend
- Jet Energie Skala in b -jets
- Signal, Untergrund, . . .

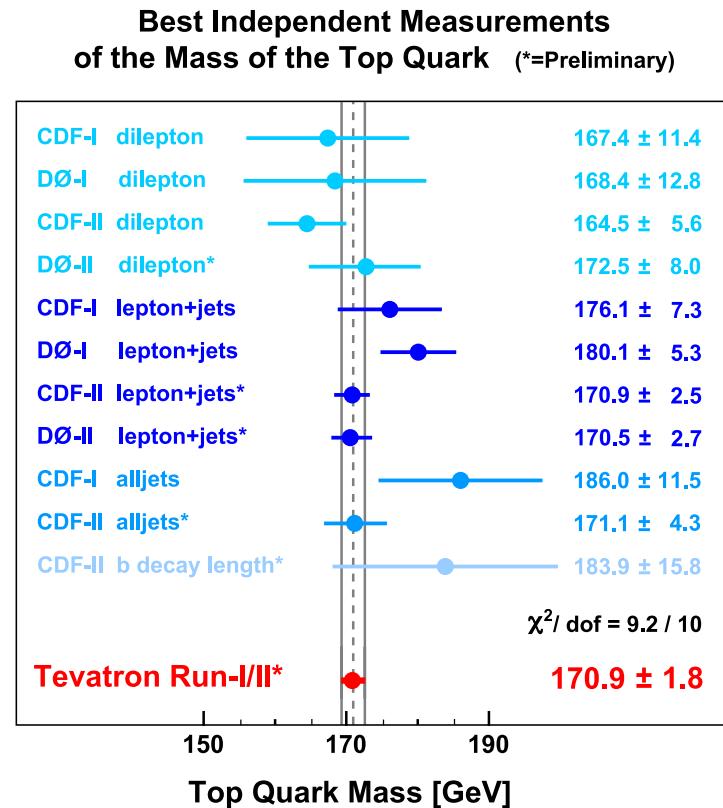
hep-ex/0703034

Aktueller Weltmittelwert

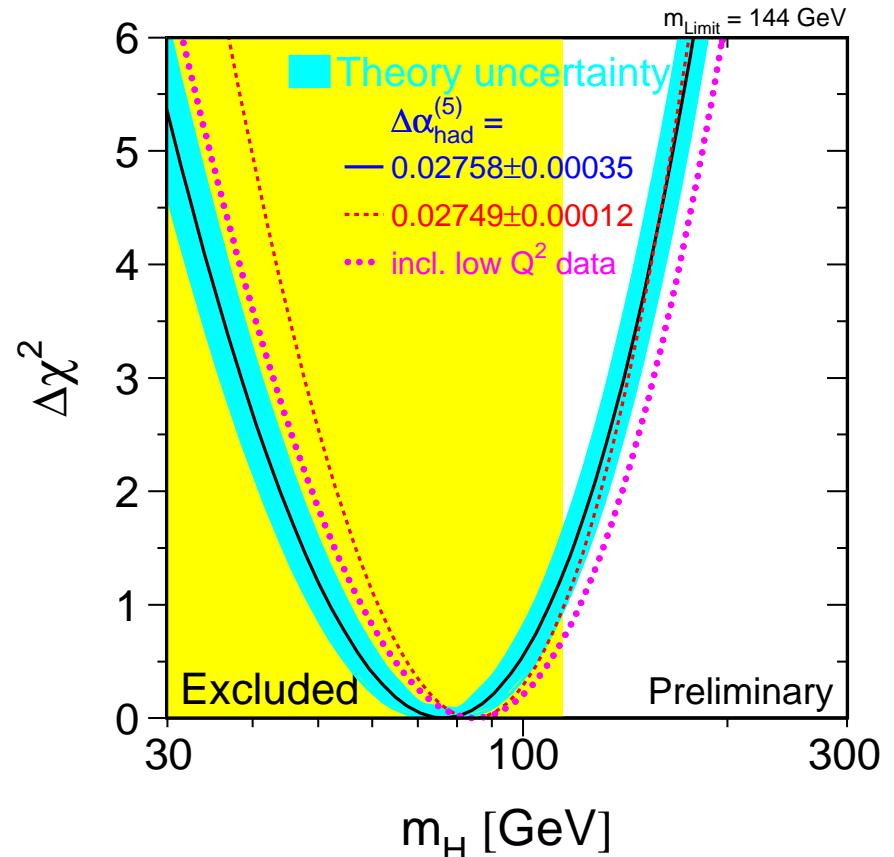
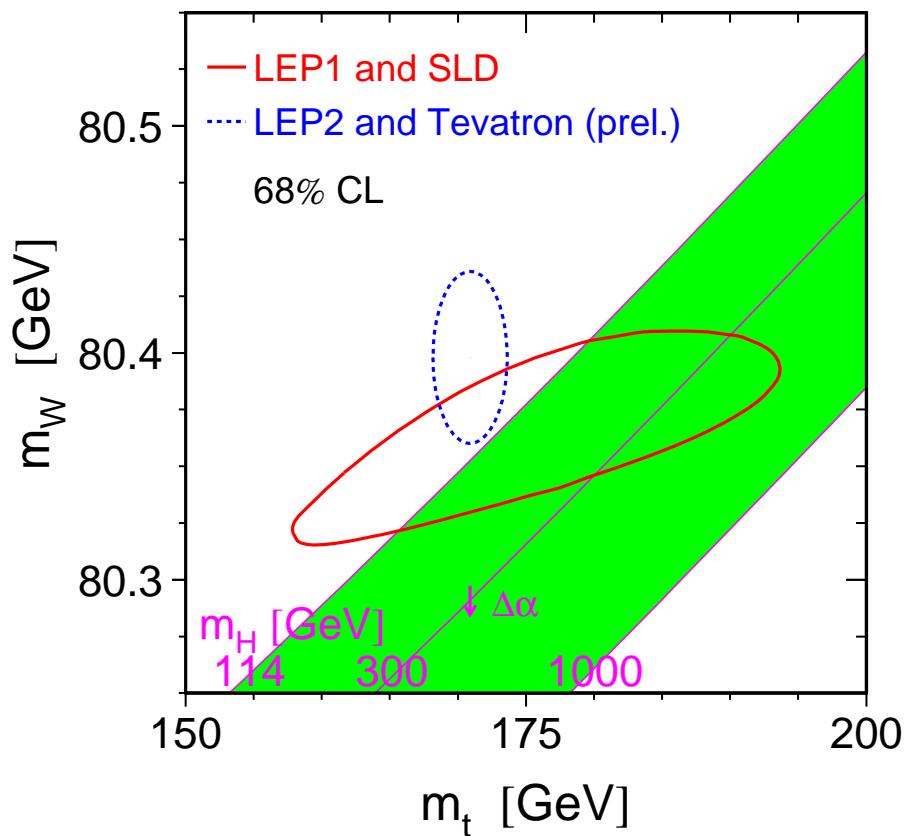
$170.9 \pm 1.1(\text{stat}) \pm 1.5(\text{syst}) \text{ GeV}$

Totale Unsicherheit: 1.8 GeV

Alljets	$172.2 \pm 4.1 \text{ GeV}$
$l+jets$	$171.2 \pm 1.9 \text{ GeV}$
dilepton	$163.5 \pm 4.5 \text{ GeV}$

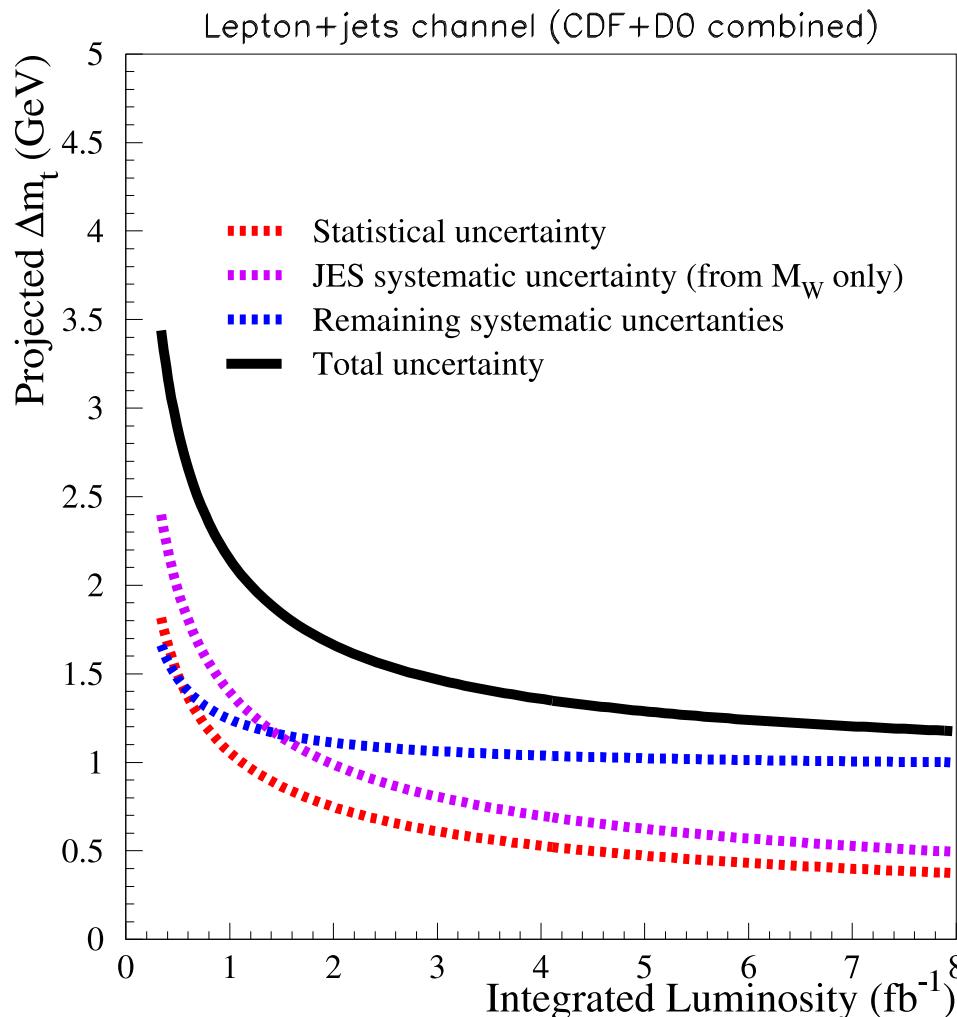


Consequences



Outlook

Tevatron



- Tevatron RunII (~2009) expected integrated Luminosity: $4 - 8 \text{ fb}^{-1}$.
- $\delta m_t \simeq 1.3 \text{ GeV} \simeq \Gamma_t$ (DØ + CDF combined)
- Jet Energy Scale no longer dominating systematics
 b -Jet Energy Scale and heavy quark background take over

Ausblick auf LHC

Wirkungsquerschnitt 100fach größer als am Tevatron.

⇒ „Low Luminosity“-Betrieb 10 Millionen Toppaare pro Jahr.

- Atlas und CMS haben die Messung der Top Masse simuliert.

Lepton + jets:

- direkte Rekonstruktion
- Anpassung mit Nebenbedingungen
- aus leptonischen Endzuständen mit J/Ψ (stat. limitiert ⇒ für high Lumi.)

Dilepton: Weighting methods.

Alljets: direkte Rekonstruktion.

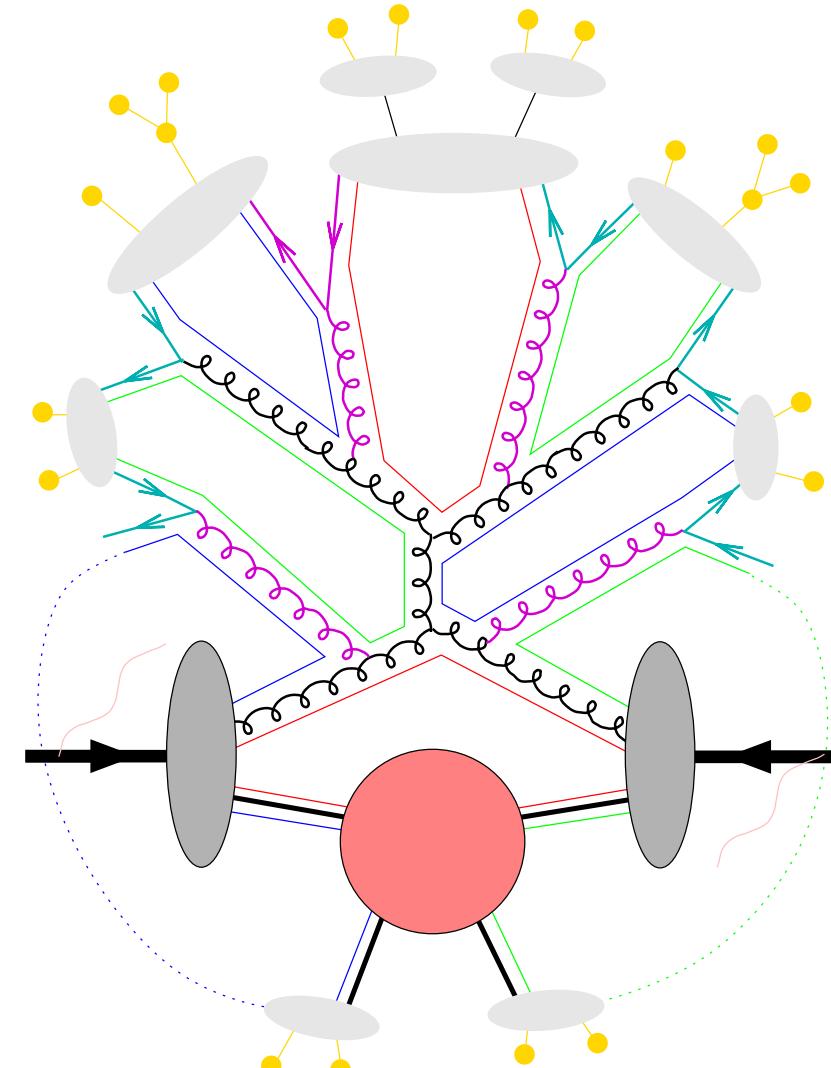
- Methoden haben unterschiedliche dominierende systematische Unsicherheiten.
- Aktuelle Studien erwarten $\delta m_t \simeq \pm 1 \text{ GeV}$

Modelling in Hadron Collisions

Overview

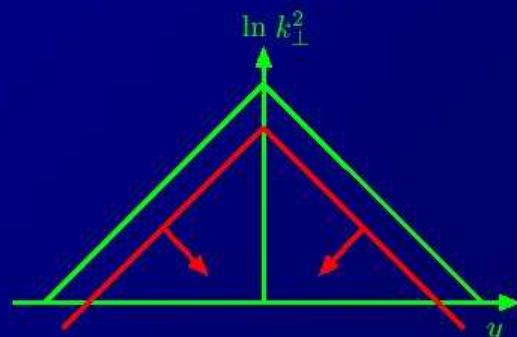
Modelling

- PDFs
- ISR
- Hard Process
 $2 \rightarrow 2(3)$, $2 \rightarrow \text{many}$; LO, NLO
- Scales
- Parton Shower
various PS; matched or unmatched
- Colour reconnection (CR)
- Hadronisation
- Decays
- Underlying Event (UE)



Some steps not computed from first principles \Rightarrow Modelling required

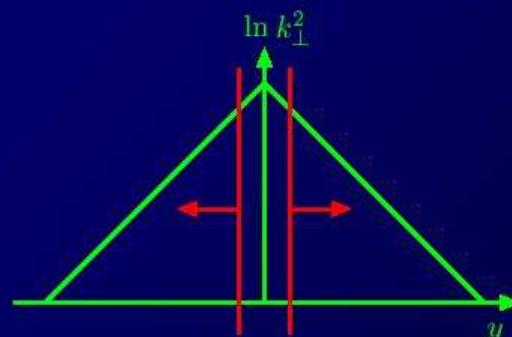
- Today, basically 2 approaches to showers:
Parton Showers (e.g. HERWIG, PYTHIA)
and Dipole Showers (e.g. ARIADNE).
- Essential difference: ordering variables.
consider e.g. gluon emission off a $q_1\bar{q}_2$ system.



PYTHIA/JETSET

m^2 ($-m^2$ for ISR)

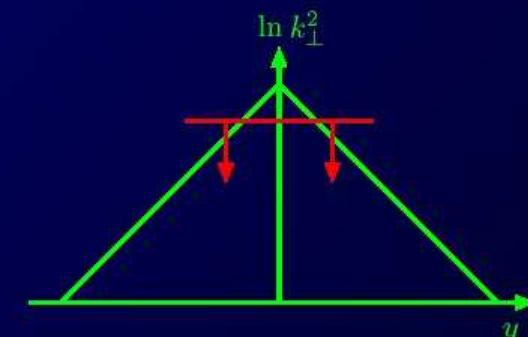
High-virtuality ems. first.



HERWIG

$\sim E^2 \theta^2$

Large-angle ems. first.



ARIADNE

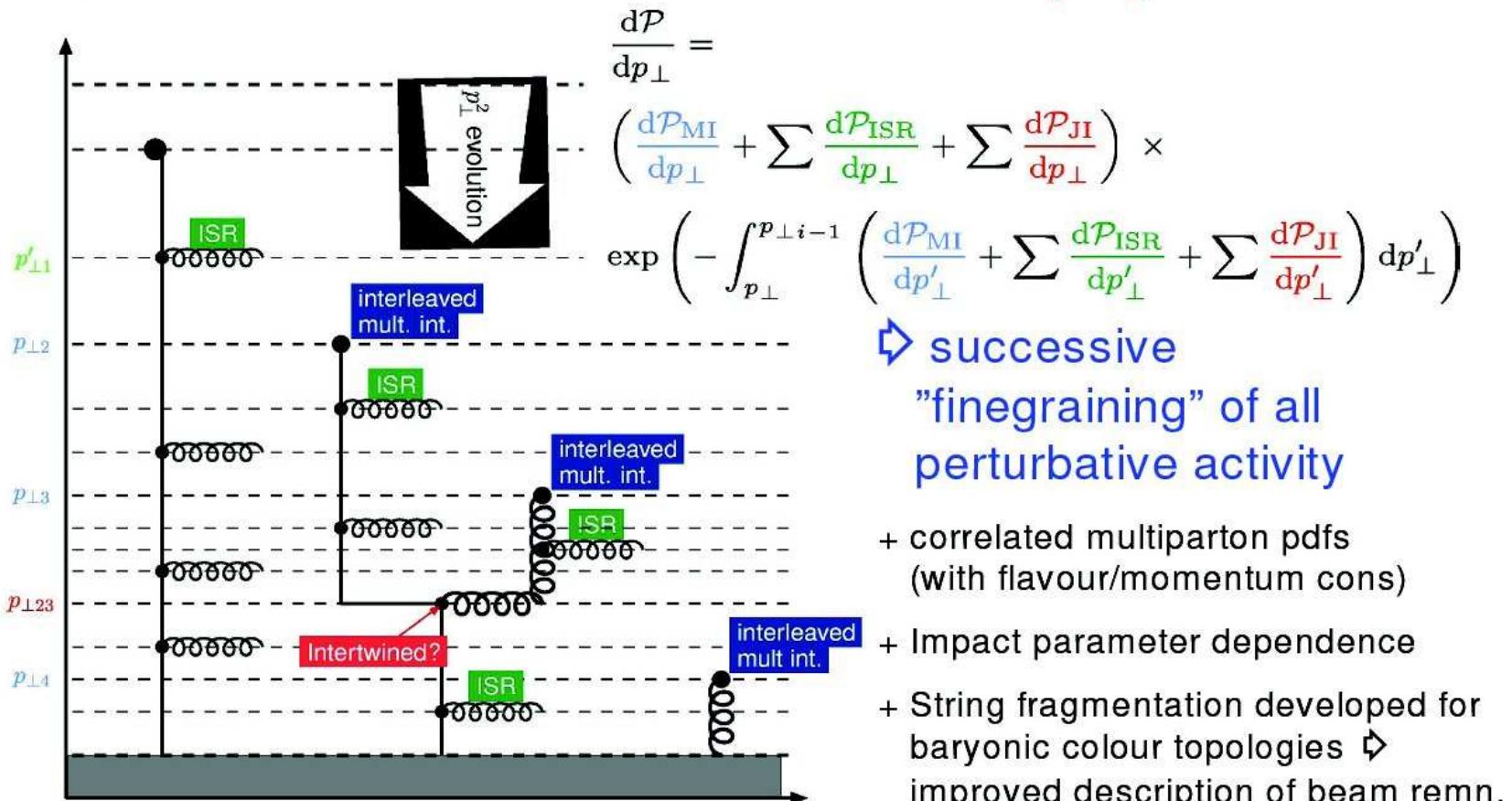
p_\perp^2

Large- p_\perp ems. first.

Pythias (new) Underlying Event Model

Peter Skands

- Parton Showers “interleaved” with Underlying Event



Colour Reconnection Models

in collab. with Peter Skands

Existing pythia tunes

Several pythia tunes to min. bias data (by R. Field) available

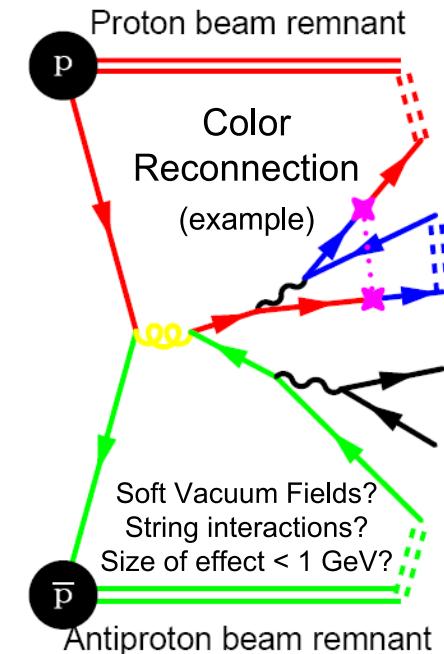
Tune A, Tune DW, Tune BW.

These implicitly allow CR within UE interaction to a high level.

New CR Models: Colour Annealing

Allow CR also within the hard interaction.

- Strings may reconnect with some probability.
- New connection chosen to minimise string length.
- Model variations: $S0$, $S1$, $S2$
differ in suppression of gluon only string loops



Tuning the Models

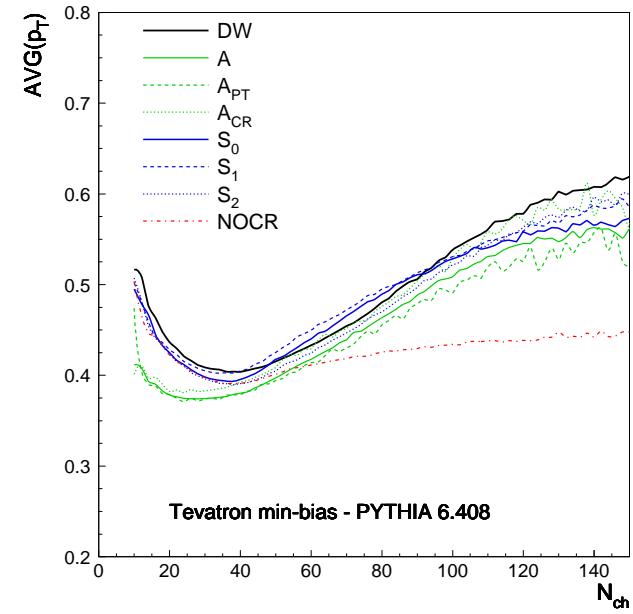
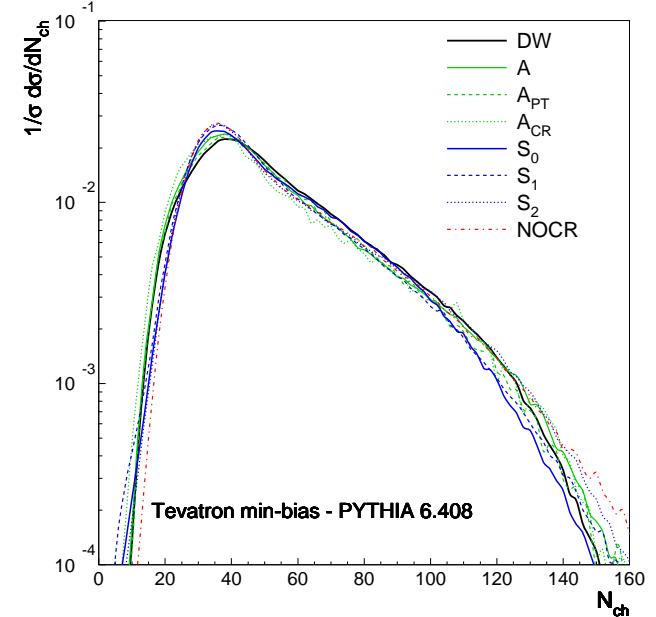
CR used in UE description \Rightarrow retune both.

Tune A is known to describe data reasonably well.

Thus models tuned to it.

- New CR models were tuned to describe N_{ch} and $\langle p_T \rangle(N_{ch})$.
- Right: comparison of models.
(Red is no CR, tuned)
- NoCR can't be made to agree:
CR seems necessary to describe UE features.

New Models w/ tunes available in Pythia 6.408+.



Influence of CR and UE

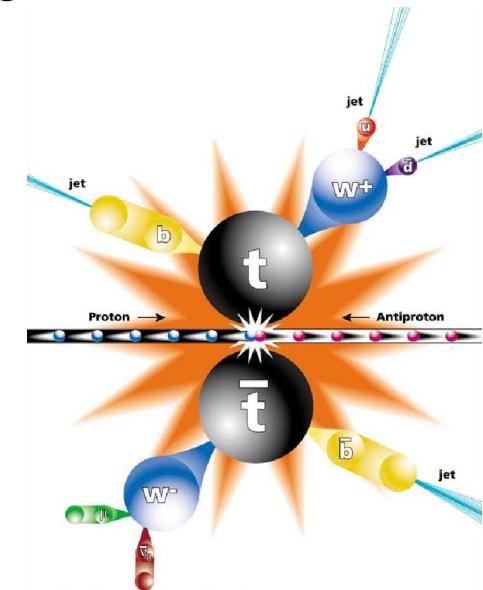
in collab. with Peter Skands

Toy Top Mass Measurement

Features of Real Mass Measurements

Current real life mass measurements contain 3 important ingredients.

- Mass estimator
 - Reconstructed physics objects
 - Jet assignment (choose or weight)
- Overall JES correction factor
- Calibration of method
 - Uses Simulation \Rightarrow may be affected by changes in CR models.



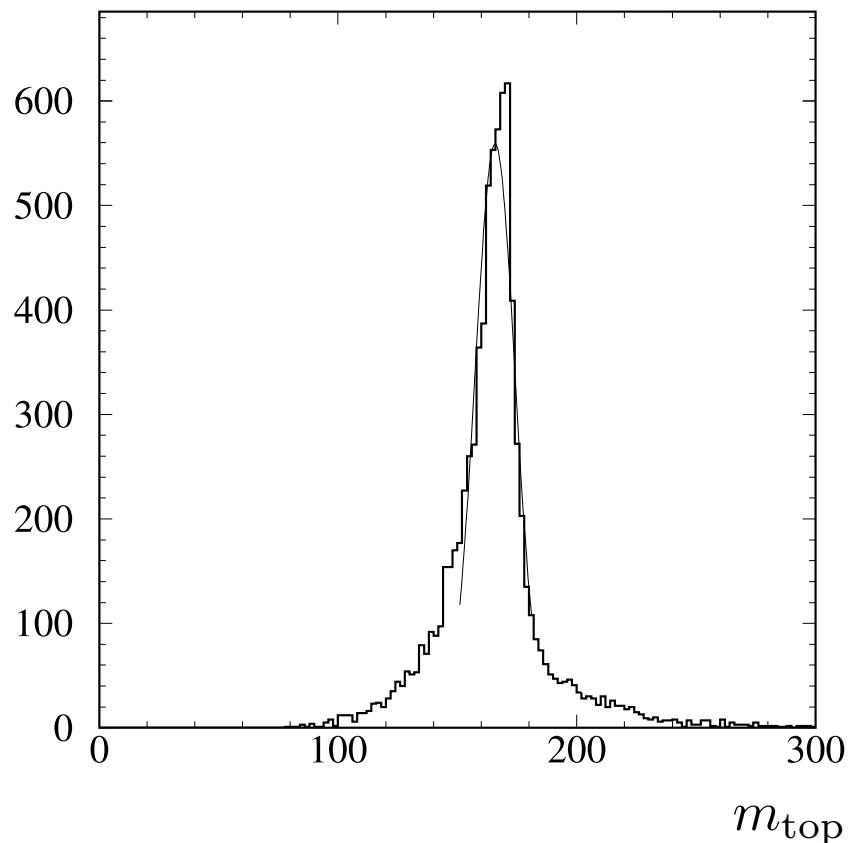
To concentrate on physics effects (and avoid dealing with detector simulation) a simplified toy mass measurement is implemented.

Toy Mass Estimator

- For each available model 100k inclusive events were generated
- Jets are reconstructed using Cone ($\Delta R = 0.5$, $p_T > 15 \text{ GeV}$)
- Exactly 4 reconstructed Jets
- Technical simplifications:
 - Generator semileptonic events.
 - Unique assignment to MC truth by ΔR possible.
- Reconstruct mass on correct assignment only: $m^2 = (p_{b\text{jet}} + p_{q\text{jet}} + p_{q'\text{jet}})^2$
(using hadronic side)

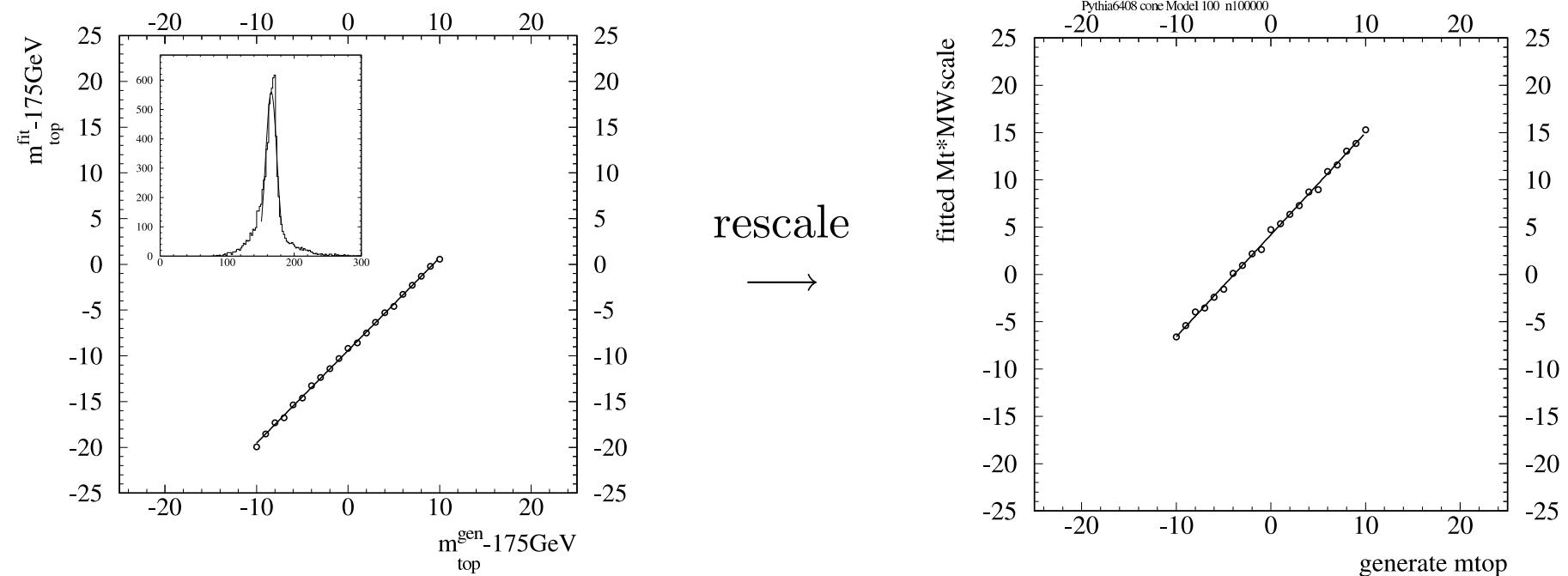
Mass Distribution

- Reconstruct mass on each event.
- Fit distribution with Gaussian: $m_{\text{top}}^{\text{fit}}$.
 - Fitrange: $\pm 15 \text{ GeV}$ (iterated to avoid bias).
 - Varied fit ranges in syst. studies.
 - Suffers from out of cone problems.
- Rescale using M_W
 - Analog to JES fitting
 - Fit W -mass from light jets
 - Scale with $s_{\text{JES}} = 80.4 \text{ GeV}/m_W$: $m_{\text{top}}^{\text{scaled}} = s_{\text{JES}} m_{\text{top}}^{\text{fit}}$



This provides two mass estimators: $m_{\text{top}}^{\text{fit}}$, $m_{\text{top}}^{\text{scaled}}$

Calibration Curves

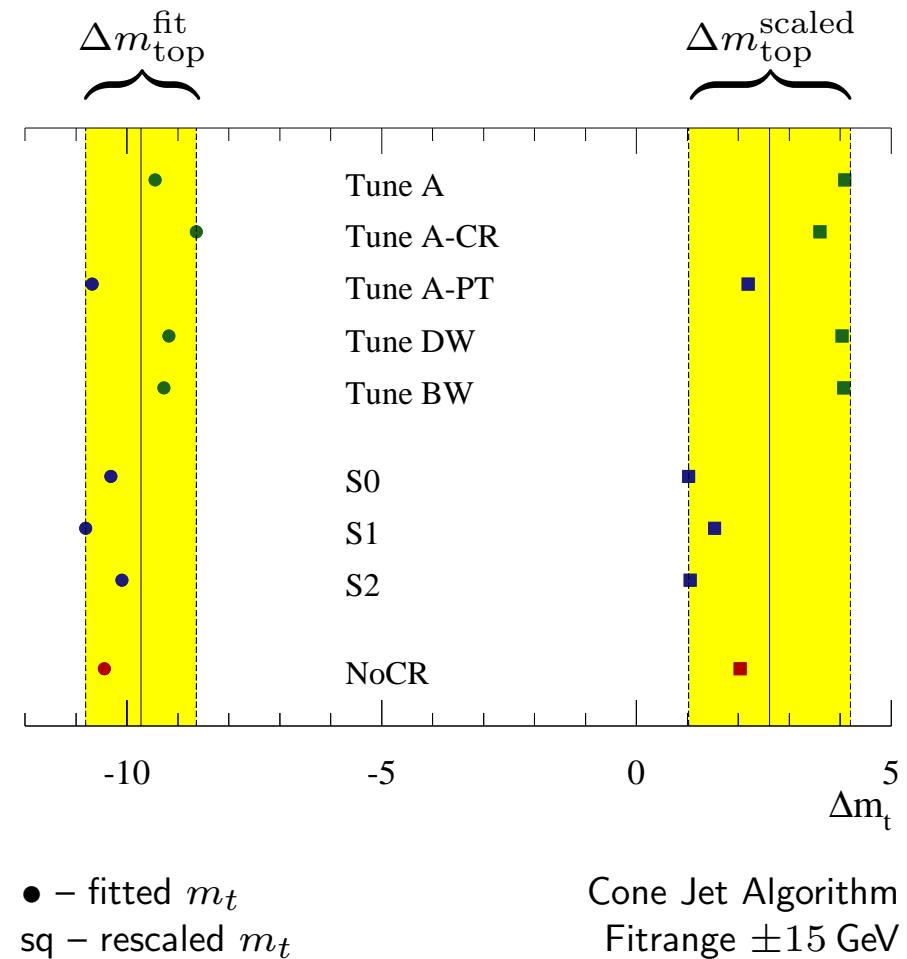


- Calibration curves show reasonably linear behaviour
- Scaling with m_W does the right thing (offset significantly reduced)
- Fit straight line to obtain offset at 175 GeV

Procedure has been repeated for a various (tuned) models **to compare offsets**

Calibration uncertainty

- Offsets and slopes normally used to calibrate measurement methods
- Model dependence is m_t uncertainty
- Spread of ± 1.5 GeV observed



Calibration uncertainty

- Offsets and slopes normally used to calibrate measurement methods

- Model dependence is m_t uncertainty

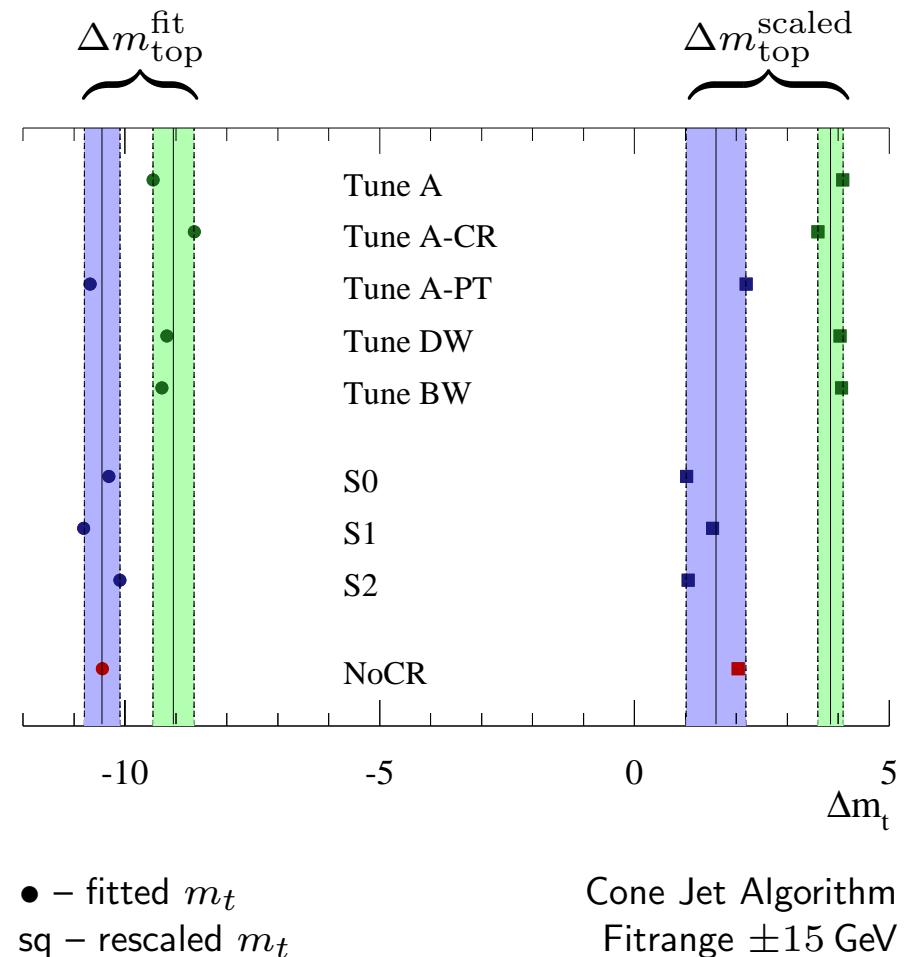
- Spread of ± 1.5 GeV observed

- 2 model classes with similar offsets

- Virtuality ordered (old) Parton Sh.
 - P_T ordered (new) Parton Shower

Significant diff. of perturbative origin

- Within each group ~ 0.5 GeV of non-perturbative nature remain.



Conclusions

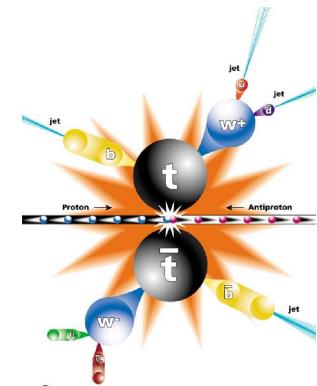
Conclusions

Top Mass Measurements

- The mass is the only free parameter in SM top physics
 - Comparison with M_W yields Higgs mass constraint.
- Several methods applied in the various decay channels
 - Lepton+jets channel is most precise
 - Combination of best Run II results:

$$170.9 \pm 1.1(\text{stat}) \pm 1.5(\text{syst}) \text{ GeV}$$

- All methods are calibrated to simulation
- What do we actually measure? Pythia parameter `pmass(6,1)`! The pole mass?
 - Dependence on new UE, CR and Parton Shower may alter meaning.



Conclusions (2)

Influence of Non-perturbative QCD Effects

- Investigated new Colour Reconnection Models for Hadron Collisions.
 - Colour reconnections seem necessary to describe underlying events.
 - UE models require retuning for different CR models.
 - Retuning performed on a variety of models.
- Studied influence of CR models on (toy) m_{top} measurements
 - Model dependence comparable to currently quoted syst. uncertainties.
 - Separable into 1 GeV perturbative and 0.5 GeV non-perturbative portion.
 - Only partly considered in current measurements.
- Sensitivity of real life top mass measurements may vary.
 - Needs investigation with full detector simulation.
 - Collaboration with CDF and DØ teams needed and planned.

hep-ph/0703081

Thanks

for the invitation and for moving my talk on short notice



Hannah Sophie *17.6.2007